

Land Settlements	0.3	0.6	0.6	0.6	0.6	0.6	0.6
Total	200.0	213.1	211.1	211.1	212.9	207.3	207.8

+ Less than 0.05 Tg CO₂ Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two year, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.s.

Table 6-16: N₂O Emissions from Agricultural Soils (Gg)

Activity	1990	2005	2006	2007	2008	2009	2010
Direct	503	546	534	538	544	523	523
Cropland	332	381	373	380	381	362	363
Grassland	170	165	161	158	163	161	161
Indirect (All Land-Use Types)	142	142	147	143	143	145	147
Cropland	121	118	125	121	121	122	124
Grassland	21	21	19	20	20	21	21
Forest Land	0	+	+	+	+	+	+
Settlements	1	2	2	2	2	2	2
Total	645	687	681	681	687	669	670

+ Less than 0.5 Gg N₂O

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Table 6-17: Direct N₂O Emissions from Agricultural Soils by Land Use Type and N Input Type (Tg CO₂ Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	103.0	118.0	115.7	117.8	118.0	112.4	112.4
Mineral Soils	100.1	115.1	112.8	114.9	115.1	109.5	109.5
<i>Mineralization and Asymbiotic Fixation</i>	<i>44.6</i>	<i>50.5</i>	<i>49.7</i>	<i>50.9</i>	<i>50.9</i>	<i>47.1</i>	<i>47.1</i>
<i>Synthetic Fertilizer</i>	<i>32.5</i>	<i>38.8</i>	<i>36.8</i>	<i>37.6</i>	<i>37.6</i>	<i>37.1</i>	<i>37.2</i>
<i>Residue N^a</i>	<i>12.4</i>	<i>13.7</i>	<i>13.8</i>	<i>13.9</i>	<i>14.3</i>	<i>13.1</i>	<i>13.1</i>
<i>Organic Amendments^b</i>	<i>10.6</i>	<i>12.1</i>	<i>12.4</i>	<i>12.5</i>	<i>12.4</i>	<i>12.2</i>	<i>12.2</i>
Organic Soils	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Grassland	52.8	51.1	49.9	49.0	50.5	49.9	49.9
Residue N ^c	12.0	11.1	10.8	10.7	11.0	10.8	10.8
PRP Manure	21.6	21.6	21.2	20.6	21.0	20.6	20.6
Synthetic Fertilizer	2.7	2.8	2.8	2.7	2.8	2.8	2.8
Managed Manure ^d	+	+	+	+	+	+	+
Sewage Sludge	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Mineralization and Asymbiotic Fixation	16.3	15.1	14.6	14.5	15.1	15.1	15.1
Total	155.8	169.1	165.6	166.8	168.5	162.2	162.3

^a Cropland residue N inputs include N in unharvested legumes as well as crop residue N.

^b Organic amendment inputs include managed manure amendments, daily spread manure amendments, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

^c Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N

^d Accounts for managed manure and daily spread manure amendments that are applied to grassland soils.

+ Less than 0.05 Tg CO₂ Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Table 6-6-18: Indirect N₂O Emissions from all Land-Use Types (Tg CO₂ Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	37.4	36.7	38.7	37.5	37.6	37.9	38.5
Volatilization & Atm. Deposition	11.5	13.0	14.3	12.6	13.0	13.7	13.9
Surface Leaching & Run-Off	25.9	23.7	24.4	24.9	24.6	24.2	24.5
Grassland	6.4	6.5	6.0	6.1	6.1	6.4	6.4
Volatilization & Atm. Deposition	5.3	5.0	5.0	4.9	4.9	4.9	4.8
Surface Leaching & Run-Off	1.0	1.5	1.1	1.2	1.2	1.5	1.5
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1
Volatilization & Atm. Deposition	+	+	+	+	+	+	+
Surface Leaching & Run-Off	+	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	0.3	0.6	0.6	0.6	0.6	0.6	0.6
Volatilization & Atm. Deposition	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Total	44.1	43.9	45.5	44.3	44.4	45.0	45.5

+ Less than 0.05 Tg CO₂ Eq.

Note: The cropland and grassland estimates for 2010 are based on the emissions from 2009. Due to limited changes in management of agricultural soils between the two years, the estimate for 2009 is expected to be representative of emissions in 2010. See the Planned Improvement section for additional details.

Figure 6-3 through Figure 6-6 show regional patterns in direct N₂O emissions, and also show N losses from volatilization, leaching, and runoff that lead to indirect N₂O emissions. Average annual emissions and N losses are shown for croplands that produce major crops and from grasslands in each state. Direct N₂O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern Minnesota, southern Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops. Direct emissions are also high in Missouri, Kansas, and Texas, primarily from irrigated cropping in western Texas, dryland wheat in Kansas, and hay cropping in eastern Texas and Missouri. Direct emissions are low in many parts of the eastern United States because a small portion of land is cultivated, and also low in many western states where rainfall and access to irrigation water are limited.

Direct emissions (Tg CO₂ Eq./state/year) from grasslands are highest in the central and western United States (Figure 6-4) where a high proportion of the land is used for cattle grazing. Some areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grassland is much lower than in the central and western United States.

Indirect emissions from croplands and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions, because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO₃⁻ leaching, N volatilization) do not respond in exactly the same manner as the processes that control direct emissions (nitrification and denitrification). For example, coarser-textured soils facilitate relatively high indirect emissions in Florida grasslands due to high rates of N volatilization and NO₃⁻ leaching, even though they have only moderate rates of direct N₂O emissions.

Figure 6-3: Major Crops, Average Annual Direct N₂O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO₂ Eq./year)

Figure 6-4: Grasslands, Average Annual Direct N₂O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO₂ Eq./year)

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N₂O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N₂O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Methodology

The 2006 IPCC Guidelines (IPCC 2006) divide the Agricultural Soil Management source category into four components: (1) direct emissions due to N additions to cropland and grassland mineral soils, including synthetic fertilizers, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from drainage and cultivation of organic cropland soils; (3) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (4) indirect emissions from soils and water due to N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N₂O.

The United States has adopted recommendations from IPCC (2006) on methods for agricultural soil management. These recommendations include (1) estimating the contribution of N from crop residues to indirect soil N₂O emissions; (2) adopting a revised emission factor for direct N₂O emissions to the extent that Tier 1 methods are used (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with the biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils based on harvest yield data to the extent that Tier 1 methods are used; (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation¹⁷⁹ (i.e., computing total emissions from managed land); and (6) reporting all emissions from managed lands, largely because management affects all processes leading to soil N₂O emissions. One recommendation from IPCC (2006) that has not been adopted is the accounting of emissions from pasture renewal, which involves occasional plowing to improve forage production. This practice is not common in the United States, and is not estimated.

The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3, process-based model (DAYCENT) was used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. The Tier 3 approach has been specifically designed and tested to estimate N₂O emissions in the United States, accounting for more of the environmental and management influences on soil N₂O emissions than the IPCC Tier 1 method (see Box 6-1 for further elaboration). The Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from non-major crops on mineral soils (e.g., barley, oats, vegetables, and other crops); (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model (i.e., federal grasslands); and (3) direct emissions from drainage and cultivation of organic cropland soils. Indirect emissions were also estimated with a combination of DAYCENT and the IPCC Tier 1 method.

EPA considered subtracting “background” emissions that would presumably occur if the lands were not managed. However, this approach is not used since (1) it is likely to be inaccurate for estimating the anthropogenic influence on soil N₂O emissions, and (2) if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions, due to the high inputs of N to agricultural soils from fertilization and legume cropping. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N₂O emissions from soils in agricultural systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N₂O emissions from each component.

[BEGIN BOX]

¹⁷⁹ N inputs from asymbiotic N fixation are not directly addressed in 2006 IPCC Guidelines, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

Box 6-1. Tier 1 vs. Tier 3 Approach for Estimating N₂O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N₂O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs and the environmental conditions at specific locations. Consequently, the Tier 3 approach is likely to produce more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (e.g., daily weather, soil types, etc.), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N₂O emissions only during that year and cannot be stored in soils and contribute to N₂O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N₂O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N added to soils is re-mineralized from soil organic matter and emitted as N₂O during subsequent years.

[END BOX]

Direct N₂O Emissions from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N₂O emissions from mineral cropland soils that are managed for production of major crops—specifically corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton—representing approximately 90 percent of total croplands in the United States. For these croplands, DAYCENT was used to simulate crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N₂O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005). Note that the influence of land-use change on soil N₂O emissions was not addressed in this analysis, but is a planned improvement.

DAYCENT simulations were conducted for each major crop at the county scale in the United States. Simulating N₂O emissions at the county scale was facilitated by soil and weather data that were available for every county with more than 100 acres of agricultural land, and by land management data (e.g., timing of planting, harvesting, and intensity of cultivation) that were available at the agricultural-region level as defined by the Agricultural Sector Model (McCarl et al. 1993). ASM has 63 agricultural regions in the contiguous United States. Most regions correspond to one state, except for those states with greater heterogeneity in agricultural practices; in such cases, more than one region is assigned to a state. While cropping systems were simulated for each county, the results best represent emissions at regional (i.e., state) and national levels due to the regional scale of management data, which include model parameters that determined the influence of management activities on soil N₂O emissions (e.g., when crops were planted/harvested).

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff,

and volatilization, as well as the processes leading to N₂O production (nitrification and denitrification). It is not possible to partition N₂O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N₂O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total of direct N₂O emissions in order to approximate the portion attributed to key practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N₂O, regardless of its source, which is unlikely to be the case (Delgado et al., 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N₂O emissions with individual sources of N.

DAYCENT was used to estimate direct N₂O emissions due to mineral N available from: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. Note that commercial organic fertilizers are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model. For the first two practices, annual changes in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), and USDA (1966, 1957, 1954, 1946). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA *Economic Research Service Cropping Practices Survey* (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).
- Managed manure production and application to croplands and grasslands: Manure N amendments and daily spread manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). Amendment data for 1997 were scaled to estimate values for other years based on the availability of managed manure N for application to soils in 1997 relative to other years. The amount of available N from managed manure for each livestock type was calculated as described in the Manure Management section (Section 6.2) and Annex 3.10.
- Retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: The IPCC approach considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DAYCENT simulations because residue production, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N₂O emissions, but these are not model inputs. The DAYCENT simulations also accounted for the approximately 3 percent of grain crop residues that were assumed to be burned based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996), and therefore did not contribute to soil N₂O emissions.
- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2000a) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002).

DAYCENT simulations produced per-area estimates of N₂O emissions (g N₂O-N/m²) for major crops in each county, which were multiplied by the cropland areas in each county to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2010a, 2010b). The emission estimates by reported crop areas in the county were scaled to the regions (and states for mapping purposes when there was more than one region in a state), and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to interannual variability in weather patterns and other controlling variables, so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions produces more accurate estimates of N₂O emissions than the Tier 1 method.

Non-Major Crop Types on Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology was used to estimate direct N₂O emissions for mineral cropland soils that are managed for production of non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, rice, peanuts, and other crops that were not included in the DAYCENT simulations. Estimates of direct N₂O emissions from N applications to non-major crop types were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers;¹⁸⁰ and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available. Consequently, non-manure organic amendments, as well as additional manure that was not added to major crops in the DAYCENT simulations, were included in the Tier 1 analysis. The influence of land-use change on soil N₂O emissions from non-major crops has not been addressed in this analysis, but is a planned improvement. The following sources were used to derive activity data:

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to non-major crops.
- A process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.
- Non-manure, non-sewage-sludge commercial organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991 through 1994; AAPFCO 1995 through 2010). Manure and sewage sludge components were subtracted from total commercial organic fertilizers to avoid double counting.
- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994, 1998, 2003, 2005, 2006, 2008, 2009, 2010a), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006). Approximately 3 percent of the crop residues were burned and therefore did not contribute to soil N₂O emissions, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006)

¹⁸⁰ Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer have been excluded to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands.

default emission factor to derive an estimate of direct N₂O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC (2006) Tier 1 methods were used to estimate direct N₂O emissions due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the *National Resources Inventory* (NRI) (USDA 2000a, as extracted by Eve 2001 and amended by Ogle 2002). Temperature data from Daly et al. (1994, 1998) were used to subdivide areas into temperate and sub-tropical climates using the climate classification from IPCC (2006). Data were available for 1982, 1992 and 1997. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions (IPCC 2006).

Direct N₂O Emissions from Grassland Soils

As with N₂O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) were combined to estimate emissions from grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, which may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate county-scale N₂O emissions from non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. Other N inputs were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the section for Major Crop Types on Mineral Cropland Soils. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (Section 6.2) and Annex 3.10. Biological N fixation is simulated within DAYCENT and therefore was not an input to the model.

Manure N deposition from grazing animals (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal and federal grasslands in each county were based on the proportion of non-federal to federal grassland area (See below for more information on area data). The amount of PRP manure applied on non-federal grasslands was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure. The remainder of the PRP manure N excretions in each county was assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for non-federal grasslands), and the N₂O emissions were estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors.

Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands were only available at the national scale, and it was not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N₂O emissions from grassland soils, and consequently, emissions from sewage sludge were estimated using the IPCC (2006) Tier 1 method.

Grassland area data were consistent with the Land Representation reported in Section 7.1. Data were obtained from the U.S. Department of Agriculture *National Resources Inventory* (USDA 2000a, Nusser and Goebel 1997) and the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD, Vogelmann et al. 2001),¹⁸¹ which were reconciled with the Forest Inventory and Analysis Data.¹⁸² The area data for pastures and rangeland were aggregated to the county level to estimate non-federal and federal grassland areas.

DAYCENT simulations produced per-area estimates of N₂O emissions (g N₂O-N/m²) for pasture and rangelands,

¹⁸¹Available online at <<http://www.mrlc.gov>>

¹⁸²Available online at <<http://fia.fs.us/tools-data/data>>

which were multiplied by the non-federal grassland areas in each county. The county-scale N₂O emission estimates for non-federal grasslands were scaled to the 63 agricultural regions (and to the state level for mapping purposes if there was more than one region in a state), and the national estimate was calculated by summing results across all regions. Tier 1 estimates of N₂O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N were produced by multiplying the N input by the appropriate emission factor. Tier 1 estimates for emissions from manure N were calculated at the state level and aggregated to the entire country but emission from sewage sludge N were calculated exclusively at the national scale.

Total Direct N₂O Emissions from Cropland and Grassland Soils

Annual direct emissions from major and non-major crops on mineral cropland soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain the total direct N₂O emissions from agricultural soil management (see Table 6-15 and Table 6-16).

Indirect N₂O Emissions from Managed Soils of all Land-Use Types

This section describes the methods used for estimating indirect soil N₂O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). Indirect N₂O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N₂O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH₃ following application of synthetic fertilizer, organic amendments (e.g., manure, sewage sludge), and deposition of PRP manure. N made available from mineralization of soil organic matter and asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N₂O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO₃⁻) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter, and asymbiotic fixation. The NO₃⁻ is subject to denitrification in water bodies, which leads to N₂O emissions. Regardless of the eventual location of the indirect N₂O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands, grasslands, forest lands, and settlements.

Indirect N₂O Emissions from Atmospheric Deposition of Volatilized N from Managed Soils

As in the direct emissions calculation, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods were combined to estimate the amount of N that was volatilized and eventually emitted as N₂O. DAYCENT was used to estimate N volatilization for land areas whose direct emissions were simulated with DAYCENT (i.e., major croplands and most grasslands). The N inputs included are the same as described for direct N₂O emissions in the sections on major crops and grasslands. Nitrogen volatilization for all other areas was estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on non-major croplands, PRP manure N excretion on federal grasslands, sewage sludge application on grasslands). The Tier 1 method and default fractions were also used to estimate N subject to volatilization from N inputs on settlements and forest lands (see the Land Use, Land-Use Change, and Forestry chapter). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N₂O emissions occurring due to re-deposition of the volatilized N (Table 6-6-18).

Indirect N₂O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method were combined to estimate the amount of N that was subject to leaching and surface runoff into water bodies, and eventually emitted as N₂O. DAYCENT was used to simulate the amount of N transported from lands used to produce major crops and most grasslands. N transport from all other areas was estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff. This N transport estimate includes N applications on croplands that produce non-major crops, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, and N inputs on settlements and forest lands. For both the DAYCENT and IPCC (2006) Tier 1 methods, nitrate leaching was assumed to be an insignificant source of indirect N₂O in cropland and grassland systems in arid regions as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation plus irrigation

does not exceed 80 percent of PET. For leaching and runoff data estimated by the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N₂O emissions that occur in groundwater and waterways (Table 6-6-18).

Uncertainty and Time-Series Consistency

Uncertainty was estimated for each of the following five components of N₂O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT; (3) direct emissions calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated with the IPCC (2006) Tier 1 method; and (5) indirect emissions calculated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N₂O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT were estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al., 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N₂O emissions were estimated with a simple error propagation approach (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.11.

Uncertainties from the Tier 1 and Tier 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006), and the results are summarized in Table 6-19. Agricultural direct soil N₂O emissions in 2010 were estimated to be between 120.2 and 255.3 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 26 percent below and 57 percent above the 2010 emission estimate of 162.3 Tg CO₂ Eq. The indirect soil N₂O emissions in 2010 were estimated to range from 23.3 to 113.9 Tg CO₂ Eq. at a 95 percent confidence level, indicating an uncertainty of 49 percent below and 150 percent above the 2010 emission estimate of 45.5 Tg CO₂ Eq.

Table 6-19: Quantitative Uncertainty Estimates of N₂O Emissions from Agricultural Soil Management in 2010 (Tg CO₂ Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO ₂ Eq.) (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N ₂ O Emissions	N ₂ O	162.3	120.2	255.3	-26%	+57%
Indirect Soil N ₂ O Emissions	N ₂ O	45.5	23.3	113.9	-49%	+150%

Note: Due to lack of data, uncertainties in areas for major crops, managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

Note: The estimates for 2010 are based on the emissions from 2009 due to limited changes in management of agricultural soils between the two years.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For quality control, DAYCENT results for N₂O emissions and NO₃⁻ leaching were compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005, Del Grosso et al. 2008), and further evaluated by comparing to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data were available for 11 sites in the United States and one in Canada, representing 30 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N₂O emissions were closer to measured values at all sites compared to the IPCC Tier 1 estimate, except for Colorado dryland cropping (Figure 6-7). In general, IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates account for site-level factors (weather, soil type) that influence N₂O emissions and produce less biased emissions estimates. Nitrate leaching data were available for three sites in the United States representing nine

different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.89 and 0.94 for annual N_2O emissions and NO_3^- leaching, respectively. This comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3^- leaching, and is an improvement over the IPCC Tier 1 method (see additional information in Annex 3.11).

Figure 6-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model

Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as were the program scripts that were used to run the Monte Carlo uncertainty analysis. Several errors were identified following re-organization of the calculation spreadsheets, and corrective actions have been taken. In particular, some of the links between spreadsheets were missing or needed to be modified. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and no errors were found.

Recalculations Discussion

County-level animal populations were updated relative to the previous Inventory report based on 2007 USDA *Census of Agriculture* data (USDA 2007), which changed the animal population estimates for 2002 through 2009. The N excretion values for cattle changed for 1990 through 2009. Waste management system (WMS) distributions for dairy and swine were updated based on Census of Agriculture farm size data (USDA 2007). The result of these changes is that N_2O emissions increased by an average of 2.0 Tg CO_2 Eq.

Planned Improvements

A key improvement is underway for the Agricultural Soil Management source category to incorporate more land-use survey data from the NRI (USDA 2000a) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1979 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records, and there are three major disadvantages to this dataset. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, which is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI provides a complete history of cropland areas for four out of every five years from 1979 to 1997, and then every year after 1998. Third, the current inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil Management methods more consistent with the methods used to estimate C stock changes for agricultural soils. The structure of model input files that contain land management data are currently being extensively revised to facilitate use of the annualized NRI data.

Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 6.5). Estimates of crop residues burned used for the Field Burning of Agricultural Residues source category will be incorporated into the DAYCENT runs for the Agricultural Soil Management source category, and reconciled in the future.

Other planned improvements are minor but will lead to more accurate estimates, including updating DAYMET weather data for more recent years following the release of new data, and using a rice-crop-specific emission factor for N amendments to rice areas.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field; composted and then applied to soils; landfilled; or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. Field burning of crop residues is not considered a net source of CO₂, because the C released to the atmosphere as CO₂ during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH₄, N₂O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). In 2010, CH₄ and N₂O emissions from field burning were 0.2 Tg CO₂ Eq. (11 Gg) and 0.1 Tg CO₂ Eq. (0.3 Gg), respectively. Annual emissions from this source over the period 1990 to 2010 have remained relatively constant, averaging approximately 0.2 Tg CO₂ Eq. (10 Gg) of CH₄ and 0.1 Tg CO₂ Eq. (0.3 Gg) of N₂O (see Table 6-20 and Table 6-21).

Table 6-20: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (Tg CO₂ Eq.)

Gas/Crop Type	1990	2005	2006	2007	2008	2009	2010
CH₄	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N₂O	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
Total	0.3	0.2	0.3	0.3	0.3	0.3	0.3

+ Less than 0.05 Tg CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 6-21: CH₄, N₂O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	2005	2006	2007	2008	2009	2010
CH₄	10	8	11	11	11	11	11
Corn	1	1	2	1	1	1	1
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	2	2	2	3	3	3	3
Soybeans	1	1	1	1	1	1	1
Sugarcane	1	1	2	1	1	2	1
Wheat	5	3	3	4	4	4	4
N₂O	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
CO	206	166	223	226	224	226	228

NO _x	19	19	34	30	29	31	30
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+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$\text{C or N released} = \sum \text{over all crop types and states (Area Burned} \div \text{Crop Area Harvested} \times \text{Crop Production} \times \text{Residue/Crop Ratio} \times \text{Dry Matter Fraction} \times \text{Burning Efficiency} \times \text{Combustion Efficiency} \times \text{Fraction of C or N})$$

where,

Area Burned	= Total area of crop burned, by state
Crop Area Harvested	= Total area of crop harvested, by state
Crop Production	= Annual production of crop in Gg, by state
Residue/Crop Ratio	= Amount of residue produced per unit of crop production, by state
Dry Matter Fraction	= Amount of dry matter per unit of biomass for a crop
Fraction of C or N	= Amount of C or N per unit of dry matter for a crop
Burning Efficiency	= The proportion of prefire fuel biomass consumed ¹⁸³
Combustion Efficiency	= The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively ¹⁸³

Crop production and area harvested were available by state and year from USDA (2010) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH₄, CO, N₂O and NO_x emissions from the field burning of agricultural residues:

$$\text{CH}_4 \text{ and CO, or N}_2\text{O and NO}_x \text{ Emissions from Field Burning of Agricultural Residues} = (\text{C or N Released}) \times (\text{Emissions Ratio for C or N}) \times (\text{Conversion Factor})$$

where,

Emissions Ratio	= g CH ₄ -C or CO-C/g C released, or g N ₂ O-N or NO _x -N/g N released
Conversion Factor	= conversion, by molecular weight ratio, of CH ₄ -C to C (16/12), or CO-C to C (28/12), or N ₂ O-N to N (44/28), or NO _x -N to N (30/14)

[BEGIN BOX]

Box 6-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Burning of Agricultural Residues were calculated using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The equation varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A

¹⁸³ In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable ‘fraction oxidized in burning.’ This variable is equivalent to (burning efficiency × combustion efficiency).

comparison of the methods and factors used in (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990-2009 Inventory to determine the magnitude of the difference in overall estimates resulting from the two approaches. The IPCC (2006) approach was not used because crop-specific emission factors for N₂O were not available for all crops. In order to maintain consistency of methodology, the IPCC/UNEP/OECD/IEA (1997) approach presented in the Methodology section was used.

The IPCC (2006) default approach resulted in 12 percent higher emissions of CH₄ and 25 percent higher emissions of N₂O than the estimates in the 1990 through 2009 Inventory. It is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current estimates are based on U.S.-specific, crop-specific, published data.

[END BOX]

Crop production data for all crops except rice in Florida and Oklahoma were taken from USDA's QuickStats service (USDA 2011). Rice production and area data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2011), and crop yields for Arkansas (USDA 2011) were applied to Oklahoma acreages¹⁸⁴ (Lee 2003 through 2006; Anderson 2008 through 2011). The production data for the crop types whose residues are burned are presented in Table 6-22. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state¹⁸⁵ from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.¹⁸⁶ McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. National-level area burned data were divided by national-level crop area harvested data to estimate the percent of crop area burned by crop. The average fraction of area burned by crop across all states is shown in Table 6-23. All crop area harvested data were from USDA (2010), except for rice acreage in Florida and Oklahoma, which is not measured by USDA (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2011; Lee 2003 through 2006; Anderson 2008 through 2011). Data on crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was assumed to be equal to the average percent area burned from the 5 years for which data were available. This average was taken at the crop and national level. Table 6-23 shows these percent area estimates aggregated for the United States as a whole, at the crop level. State-level estimates based on state-level crop area harvested and burned data were also prepared, but are not presented here.

All residue/crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützel (1987). The datum for sugarcane is from Kinoshita (1988) and that of cotton from Huang et al. (2007). The residue/crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützel (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). These data are listed in Table 6-24. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and

¹⁸⁴ Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

¹⁸⁵ Alaska and Hawaii were excluded.

¹⁸⁶ McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general "other crops/fallow" category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and "other" categories.

the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). Emission ratios and conversion factors for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-22: Agricultural Crop Production (Gg of Product)

Crop	1990	2005	2006	2007	2008	2009	2010
Corn ^a	201,534	282,263	267,503	331,177	307,142	333,011	316,165
Cotton	3,376	5,201	4,700	4,182	2,790	2,654	3,942
Lentils	40	238	147	166	109	266	393
Rice	7,114	10,132	8,843	9,033	9,272	9,972	11,027
Soybeans	52,416	83,507	87,001	72,859	80,749	91,417	90,610
Sugarcane	25,525	24,137	26,820	27,188	25,041	27,608	24,821
Wheat	74,292	57,243	49,217	55,821	68,016	60,366	60,103

^a Corn for grain (i.e., excludes corn for silage).

Table 6-23: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2006	2007	2008	2009	2010
Corn	+	+	+	+	+	+	+
Cotton	1	1	1	1	1	1	1
Lentils	1	+	1	1	1	1	1
Rice	10	6	10	13	10	10	10
Soybeans	+	+	+	+	+	+	+
Sugarcane	32	18	47	21	32	32	32
Wheat	2	2	2	2	2	2	2

+ Less than 0.5 percent

Table 6-24: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 6-25: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH ₄ :C	0.005 ^a	16/12
CO:C	0.060 ^a	28/12
N ₂ O:N	0.007 ^b	44/28
NO _x :N	0.121 ^b	30/14

^a Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).

^b Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

Uncertainty and Time-Series Consistency

Due to data and time limitations, uncertainty resulting from the fact that emissions from burning of Kentucky bluegrass and “other” residues are not included in the emissions estimates was not incorporated into the uncertainty analysis. The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-26. Methane emissions from field burning of agricultural residues in 2010 were estimated to be between 0.14 and 0.32 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 42 percent above the 2010 emission estimate of 0.23 Tg CO₂ Eq. Also at the 95 percent confidence level, N₂O emissions were estimated to be between 0.07 and 0.13 Tg CO₂ Eq. (or approximately 29 percent below and 31 percent above the 2010 emission estimate of 0.10 Tg CO₂ Eq.).

Table 6-26: Tier 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (Tg CO₂ Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH ₄	0.23	0.14	0.32	-40%	42%
Field Burning of Agricultural Residues	N ₂ O	0.10	0.07	0.13	-29%	31%

^aRange of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. For some crops and years in Florida and Oklahoma, the total area burned as measured by McCarty (2010) was greater than the area estimated for that crop, year, and state by Gonzalez (2004-2008) and Anderson (2007) for Florida and Oklahoma, respectively, leading to a percent area burned estimate of greater than 100 percent. In such cases, it was assumed that the percent crop area burned for that state was 100 percent.

Recalculations Discussion

For the current Inventory, the crop production data for 2009 and 2010 were updated relative to the previous report using data from USDA (2011). Rice cultivation data for Florida and Oklahoma, which are not reported by USDA, were updated for 2010 through communications with state experts. The methodology was revised to sum state-level crop area burned and state-level crop area harvested data to determine a national percentage of crop area burned. Previously, the percentage of crop area burned was determined at the state-level and then the state percentages were averaged. This update was made to improve accuracy and accommodate uncertainty calculations. These updates resulted in an 8.6 percent decrease in sector emissions in 2009, and an average decrease in emissions of 14.2 percent from 1990 to 2009.

Planned Improvements

Attempts will be made to incorporate state-level estimates of percentage of crop area burned into the uncertainty analysis next year to make the uncertainty analysis more robust. Further investigation will be also made into inconsistent data from Florida and Oklahoma as mentioned in the QA/QC and verification section, and attempts will be made to revise or further justify the assumption of 100 percent of area burned for those crops and years where the estimated percent area burned exceeded 100 percent. The availability of useable area harvested and other data for bluegrass and the “other crops” category in McCarty (2010) will also be investigated, in order to try to incorporate these emissions into the estimate.

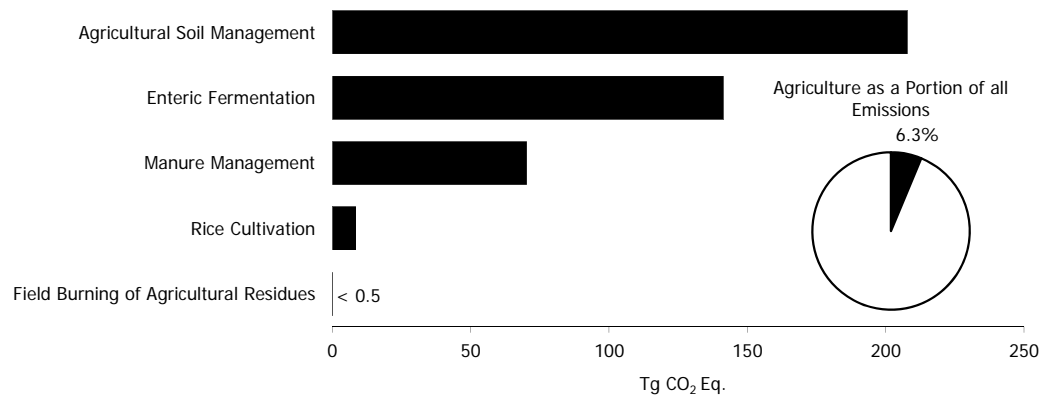


Figure 6-1: 2010 Agriculture Chapter Greenhouse Gas Sources

Figure 6-2

Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management

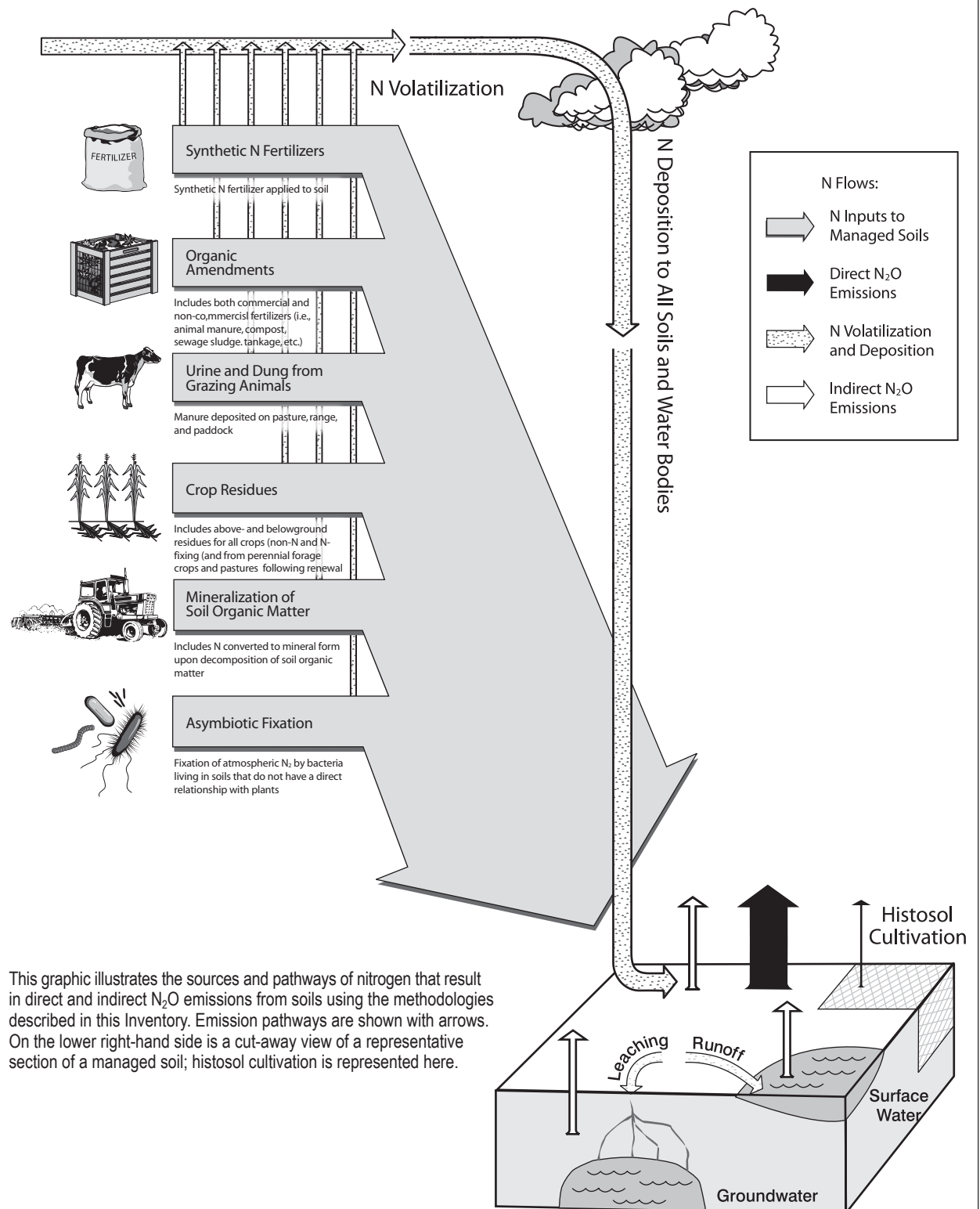


Figure 6-3

Major Crops, Average Annual Direct N₂O Emissions Estimated Using the DAYCENT Model, 1990-20%
(Tg CO₂ Eq/year)

